

# Gravitational-wave observations by advanced LIGO and VIRGO

LIGO Scientific and Virgo Collaboration

DOI:

[10.1088/1742-6596/1468/1/012218](https://doi.org/10.1088/1742-6596/1468/1/012218)

License:

Creative Commons: Attribution (CC BY)

*Document Version*

Publisher's PDF, also known as Version of record

*Citation for published version (Harvard):*

LIGO Scientific and Virgo Collaboration 2020, 'Gravitational-wave observations by advanced LIGO and VIRGO', *Journal of Physics: Conference Series*, vol. 1468, no. 1, 012218. <https://doi.org/10.1088/1742-6596/1468/1/012218>

[Link to publication on Research at Birmingham portal](#)

## General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

## Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact [UBIRA@lists.bham.ac.uk](mailto:UBIRA@lists.bham.ac.uk) providing details and we will remove access to the work immediately and investigate.

PAPER • OPEN ACCESS

## Gravitational-Wave Observations by Advanced LIGO and Virgo

To cite this article: P Schmidt and for the LIGO Scientific and Virgo Collaboration 2020 *J. Phys.: Conf. Ser.* **1468** 012218

View the [article online](#) for updates and enhancements.



**IOP | ebooks™**

Bringing together innovative digital publishing with leading authors from the global scientific community.

Start exploring the collection—download the first chapter of every title for free.

# Gravitational-Wave Observations by Advanced LIGO and Virgo

P Schmidt<sup>1</sup> for the LIGO Scientific and Virgo Collaboration

<sup>1</sup> School of Physics and Astronomy and Institute for Gravitational Wave Astronomy, University of Birmingham, Edgbaston, B15 2TT, United Kingdom

E-mail: [pschmidt@star.sr.bham.ac.uk](mailto:pschmidt@star.sr.bham.ac.uk)

**Abstract.** From September 2015 until August 2017, the Advanced LIGO and Virgo gravitational-wave detectors conducted their first two observing runs O1 and O2. Since the milestone detection of gravitational waves from two coalescing black holes, GW150914, a further nine binary black holes collisions as well as one binary neutron star inspiral have been identified, firmly establishing the field of gravitational-wave astronomy. After a commissioning break, the third observing run commenced on April 1, 2019 which has since seen the public announcement of several tens of gravitational-wave candidate events. In this proceedings, we summarise the observations during O1 and O2 and briefly discuss the current status.

## 1. Introduction

Coalescing compact binaries are amongst the strongest emitters of gravitational waves (GWs) with frequencies accessible to current ground-based GW detectors. The observation of the GWs from such merger events allows us to shed light on binary formation channels, enable precision tests of General Relativity in its strong-field regime, and open up new avenues of astronomy research.

During the first observing run (O1) of Advanced LIGO, which took place from September 12<sup>th</sup>, 2015 until January 19<sup>th</sup>, 2016 the first observations of GWs from stellar-mass binary black holes (BBH) [1, 2, 3, 4] were made. The second observing run (O2) of the Advanced LIGO detectors [5] commenced on November 30<sup>th</sup>, 2016, and ended on August 25<sup>th</sup>, 2017. On August 1<sup>st</sup>, 2017 the Advanced Virgo detector [6] joined O2, enabling the first three-detector observations of GWs [7, 8].

The current network of ground-based interferometers is particularly sensitive to GWs from the inspiral, merger and ringdown of compact binaries in a frequency range between 15 Hz and a few kHz. In total, the first two observing runs have seen eleven confident detections of GWs, ten from BBH mergers and one from a binary neutron star (BNS) signal: GW150914, GW151012, GW151226, GW170104, GW170608, GW170729, GW170809, GW170814, GW170818, GW170823 and GW170817 [9].

These eleven GW events were identified by two matched-filter searches [10, 11, 12, 13], using relativistic models of GWs from compact binary mergers, as well as one unmodeled search for short-duration transient signals (bursts) [14].

GWs from compact binaries carry information about the characteristic properties of the source such as the masses and spins. These are extracted via Bayesian inference by using theoretical

models of the GW signal that describe the inspiral, merger and ringdown of the final object for BBH [15, 16, 17, 18, 19, 20, 21, 22], and the inspiral (and merger) for BNS [23, 24, 25]. Such models are built by combining post-Newtonian calculations [26, 27, 28, 29, 30], the effective-one-body formalism [31, 32, 33, 34, 35, 36] and numerical relativity [37, 38, 39, 40, 41, 42]. Based on a variety of theoretical models, we estimate the total mass of GW170729 to be  $84.4^{+15.8}_{-11.1} M_{\odot}$ , making it the heaviest BBH observed to date. GW170818 is the second BBH observed in triple-coincidence between the two LIGO observatories and Virgo after GW170814 [7]. As the sky location is primarily determined by the differences in the times of arrival of the GW signal at the different detector sites, LIGO-Virgo coincident events have a vastly improved sky localization, which is crucial for electromagnetic (EM) follow-up campaigns [43, 44, 45, 46].

The observation of these GW events allows us to place constraints on the rates of stellar-mass BBH and BNS mergers in the Universe and probe their mass and spin distributions, putting them into astrophysical context. For BBH we find a merger rate of  $9.7 - 101 \text{ Gpc}^{-3} \text{y}^{-1}$ ; for BNS  $110 - 3840 \text{ Gpc}^{-3} \text{y}^{-1}$ . The non-observation of GWs from a neutron star – black hole binary yields a strong 90% upper limit of  $610 \text{ Gpc}^{-3} \text{y}^{-1}$ . The details of the calculation and the astrophysical implications of these observations are discussed in Refs. [9] and [47] respectively.

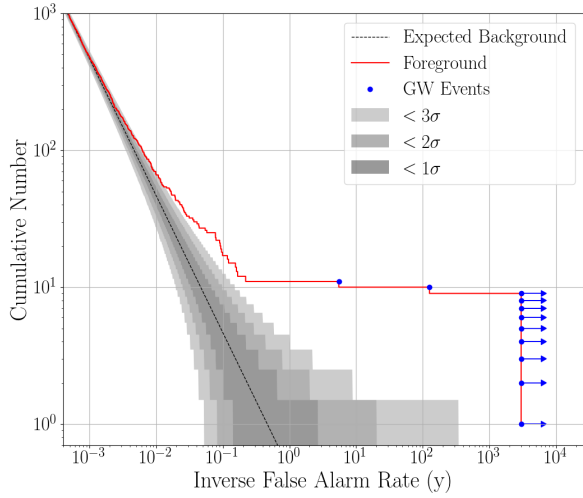
For complete information on the events discussed here, including data products, we direct the reader to the GWTC-1 catalog paper<sup>1</sup> [9], references therein and the Gravitational Wave Open Science Center [52].

## 2. Gravitational-wave observations during O1 and O2

The eleven GW detections were identified by three searches that analysed noise-subtracted coincident strain data from the three interferometers. The two matched-filter searches target GWs from compact binaries with a redshifted total mass of  $2-500 M_{\odot}$ , a mass ratio between 1 and 1:98, and with maximal dimensionless spins of 0.998 for black holes (BHs) and 0.05 for neutron stars (NSs). The burst search does not use waveform models to compare against the data, but instead identifies regions of excess power in the time-frequency representation of the gravitational strain, and is optimised for the detection of compact binaries with a total mass less than  $100 M_{\odot}$ . Each search identifies coincident candidate events (triggers) that are ranked by their statistical significance, which is quantified by the inverse false-alarm-rate (IFAR). All coincident triggers with a false-alarm-rate less than 1 per 30 days and a probability of astrophysical origin  $> 50\%$ , are designated as confident GW detections. Figure 1 shows the observed distribution of events as a function of the IFAR, as well as the expected background and the Poisson uncertainty bands for one of the matched filter searches. The foreground distribution, i.e. the eleven GW events, clearly stand out from the background.

The GW signal emitted by compact binary mergers depends on a set of intrinsic and extrinsic parameters that fully characterise the source. In General Relativity, astrophysical black holes are fully described by their mass  $m$  and (dimensionless) spin angular momentum vector  $\vec{\chi}$ . Neutron stars depend on additional intrinsic parameters related to the nuclear equation of state (EoS) of the matter they are made of. Observing the GWs emitted by compact binaries and comparing them to theoretical signal models allows us to infer the source parameters. For low-mass binaries the best measured mass parameter is the chirp mass  $\mathcal{M}_c := (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$ , where  $m_1$  and  $m_2$  denote the component mass of each binary companion. For more massive binaries, the total mass,  $M = m_1 + m_2$ , is measured best. In current observations, the individual spins are poorly constrained but the dominant spin effects are captured by a single effective inspiral spin parameter [15, 53],  $\chi_{\text{eff}} := (m_1 \chi_{1L} + m_2 \chi_{2L}) / M$ , where  $\chi_{iL}$  denotes the spin component parallel to the orbital angular momentum. The source parameters are inferred via Bayesian

<sup>1</sup> We note that independent analyses of the publicly available GW strain data have been conducted. Results from these analyses can be found in Refs. [48, 49, 50, 51].



**Figure 1.** Cumulative histogram of search results for one of the matched-filter searches, GstLAL [12, 13], as a function of IFAR. The dashed line shows the expected background. The shaded regions indicate sigma Poisson uncertainty bounds. The blue dots are the eleven GW events found by the search. Events with a measured or bounded IFAR greater than 3000 years are indicated by an arrow. Figure adapted from Ref. [9].

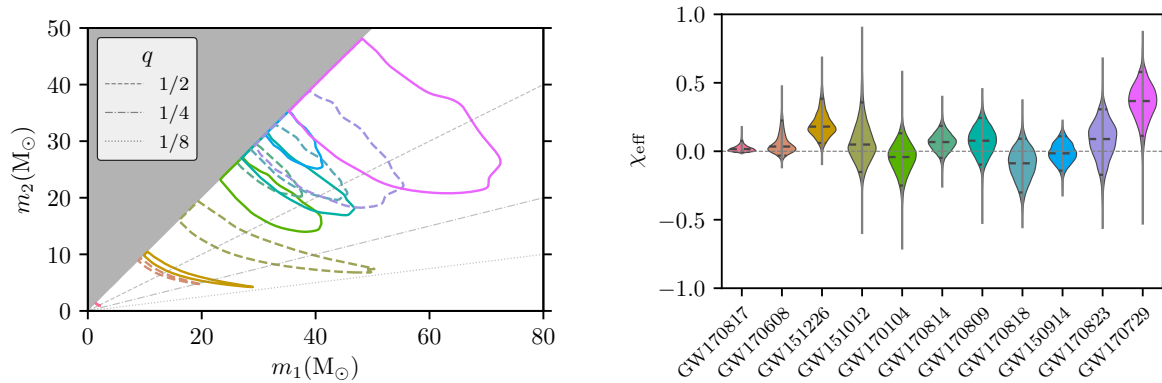
inference [54] by comparing a variety of theoretical, general relativistic waveform models against the data. Some key parameters such as the component masses and the effective inspiral spin are shown in Fig. 2.

The observed black hole binaries span a wide range of total source-frame masses, from GW170608, the lightest BBH with  $18.6^{+3.2}_{-0.7} M_{\odot}$  to GW170729, the heaviest BBH with  $84.4^{+15.8}_{-11.1} M_{\odot}$ . In particular, the heavy black holes observed raise interesting questions regarding their possible formation process and history. However, no black holes in either the upper or lower mass gap have been identified in the first two observing runs [55, 56, 57, 58]. Further, all ten BBH observations are consistent with equal mass.

The black hole spins are more difficult to constrain as their effects on the GW signal are of higher post-Newtonian order but they are of particular interest for the discrimination between different binary formation scenarios. The currently best measured spin-related quantity is the effective inspiral spins,  $\chi_{\text{eff}}$ , whose measurements are shown in the right panel of Fig. 2. Apart from GW170729, and marginally also for GW151226, a vanishing or small  $\chi_{\text{eff}}$  is consistent with the data for the majority of events. Possible misalignment between the orbital angular momentum and the black holes spins, which induces precession [59, 60], is currently unconstrained but future observations may yield the first measurements of precession.

The observation of GWs from merging BBH allows us to probe the predictions of General Relativity in the previously unexplored highly dynamical strong-field and strong-curvature regime. The current observations are all found to be consistent with Einstein's theory of gravity [61], but as the uncertainties on the measurements decrease in future observations, deviations from GR or signs of exotic physics may be uncovered.

The first two observing runs did not only bring ten BBHs but also the historic observation of GWs from a binary neutron star inspiral, GW170817 [8]. To date, thousands of neutron stars have been observed electromagnetically, yet little is known about the matter they are made of: Their interior is thought to be made of cold, ultradense matter – conditions very difficult to achieve in laboratory experiments [62]. The observation of GWs from a binary neutron star, however, provides a unique means to probe the nature of matter under such extreme conditions and infer the as of yet unknown equation of state (EoS). This is possible as the presence of matter modifies the GW signal in comparison to that of a BBH due to the tidal response of the star. The additional signature induced in the GW depends on the EoS through a macroscopic parameter known as the tidal deformability  $\tilde{\Lambda}$  [63]. The observation of GW170817 has allowed us to put the



**Figure 2.** Left: 90% credible regions of the two-dimensional posterior probability density (PDF) for the inferred source component masses for all eleven GW events. Right: One-dimensional PDF for the effective inspiral spin, where the horizontal lines indicate the mean and the 90% bounds. Adapted from Ref. [9]

first direct constraint on the tidal deformability and thereby on the EoS [64, 65]. The analysis of GW170817 finds that soft EoSs, which yield rather compact NSs, are preferred. [65, 66]. The observation of more GWs from binary neutron stars will allow us to populate the famous mass-radius diagram and zoom in on the true EoS.

GW170817 is one of the most observed events in astronomy. Shortly after the GW was detected, a gamma-ray burst was registered in a region of the sky consistent with GW170817 [45]. It is the first example of multi-messenger astronomy combining observations in GWs, the entire electromagnetic, cosmic rays and neutrinos. This joint observation has confirmed the long-standing hypothesis that some short gamma-ray bursts are caused by binary neutron star mergers and that the subsequent EM counterpart is a kilonova [67]. Moreover, the joint GW-EM observation has allowed to use GW170817 as a standard siren and make a first Hubble constant measurement with GWs [68].

### 3. O3 and beyond

After a commissioning period during which the two LIGO detectors and Virgo underwent significant upgrades to improve their respective sensitivities, the third observing run (O3) began on April 1, 2019. Different to the previous two observing runs, GW candidate events, which are above a certain significance threshold, are immediately shared with the scientific community in order to enable low-latency follow up. As of October 2019, a total of 33 detection candidates were shared publicly. These candidates were identified in low-latency by matched filter searches and, as for previous runs, will be thoroughly analysed offline.

Candidates of particular interest include a neutron star – black hole candidate from August 14, S190814bv, as well as a binary neutron star candidate, S190425z, from April 25, 2019. In addition, on August 29, two binary black hole candidates were identified within around 20 minutes of each other. The complete list of public alerts can be obtained from the Gravitational-Wave Candidate Event Database [69].

O3 is scheduled to last for one year. Recently, the Japanese GW detector KAGRA [70] has achieved its first periods with a locked interferometer and is aiming to join O3 either later this year or early in 2020. Even though KAGRA is expected to join the GW detector network with a significantly lower sensitivity than that of the currently operating facilities, a fourth detector operating will increase the duty cycle and, for close events, help to improve the sky



localisation [71], which is crucial for EM follow-up.

After a further upgrade, LIGO, Virgo and KAGRA are anticipated to achieve their full design sensitivity for O4, currently scheduled for late 2021. Further upgrades and possibly a fifth GW observatory in India, promise hundreds of GW detections in the years to come.

## Acknowledgments

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación, the Vicepresidència i Conselleria d'Innovació, Recerca i Turisme and the Conselleria d'Educació i Universitat del Govern de les Illes Balears, the Conselleria d'Educació, Investigació, Cultura i Esport de la Generalitat Valenciana, the National Science Centre of Poland, the Swiss National Science Foundation (SNSF), the Russian Foundation for Basic Research, the Russian Science Foundation, the European Commission, the European Regional Development Funds (ERDF), the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the Paris Île-de-France Region, the National Research, Development and Innovation Office Hungary (NKFIH), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the Natural Science and Engineering Research Council Canada, the Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, Innovations, and Communications, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Leverhulme Trust, the Research Corporation, the Ministry of Science and Technology (MOST), Taiwan and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, MPS, INFN, CNRS and the State of Niedersachsen/Germany for provision of computational resources. This document is LIGO-P1900339.

## References

- [1] Abbott B P *et al.* (LIGO Scientific, Virgo) 2016 *Phys. Rev. Lett.* **116** 061102 (*Preprint* [1602.03837](#))
- [2] Abbott B P *et al.* (LIGO Scientific, Virgo) 2016 *Phys. Rev. Lett.* **116** 241103 (*Preprint* [1606.04855](#))
- [3] Abbott B P *et al.* (LIGO Scientific, Virgo) 2016 *Phys. Rev. D* **93** 122003 (*Preprint* [1602.03839](#))
- [4] Abbott B P *et al.* (LIGO Scientific, Virgo) 2016 *Phys. Rev. X* **6** 041015 (*Preprint* [1606.04856](#))
- [5] Aasi J *et al.* (LIGO Scientific Collaboration) 2015 *Class. Quant. Grav.* **32** 074001 (*Preprint* [1411.4547](#))
- [6] Acernese F *et al.* (Virgo Collaboration) 2015 *Class. Quant. Grav.* **32** 024001 (*Preprint* [1408.3978](#))
- [7] Abbott B P *et al.* (Virgo, LIGO Scientific) 2017 *Phys. Rev. Lett.* **119** 141101 (*Preprint* [1709.09660](#))
- [8] Abbott B P *et al.* (Virgo, LIGO Scientific) 2017 *Phys. Rev. Lett.* **119** 161101
- [9] Abbott B P *et al.* (LIGO Scientific, Virgo) 2019 *Phys. Rev.* **X9** 031040 (*Preprint* [1811.12907](#))
- [10] Nitz A H *et al.* 2017 PyCBC Software [github.com/ligo-cbc/pycbc](https://github.com/ligo-cbc/pycbc)
- [11] Usman S A *et al.* 2016 *Class. Quant. Grav.* **33** 215004 (*Preprint* [1508.02357](#))
- [12] Sachdev S *et al.* 2019 (*Preprint* [1901.08580](#))

- [13] Messick C *et al.* 2017 *Phys. Rev. D* **95** 042001 (Preprint [1604.04324](#))
- [14] Klimenko S *et al.* 2016 *Phys. Rev. D* **93** 042004 (Preprint [1511.05999](#))
- [15] Ajith P *et al.* 2011 *Phys. Rev. Lett.* **106** 241101 (Preprint [0909.2867](#))
- [16] Santamaría L *et al.* 2010 *Phys. Rev. D* **82** 064016 (Preprint [1005.3306](#))
- [17] Hannam M *et al.* 2014 *Phys. Rev. Lett.* **113** 151101 (Preprint [1308.3271](#))
- [18] Khan S *et al.* 2016 *Phys. Rev. D* **93** 044007 (Preprint [1508.07253](#))
- [19] Pan Y *et al.* 2014 *Phys. Rev. D* **89** 084006 (Preprint [1307.6232](#))
- [20] Taracchini A *et al.* 2014 *Phys. Rev. D* **89** 061502 (Preprint [1311.2544](#))
- [21] Bohé A *et al.* 2017 *Phys. Rev. D* **95** 044028 (Preprint [1611.03703](#))
- [22] Babak S, Taracchini A and Buonanno A 2017 *Phys. Rev. D* **95** 024010 (Preprint [1607.05661](#))
- [23] Hinderer T *et al.* 2016 *Phys. Rev. Lett.* **116** 181101 (Preprint [1602.00599](#))
- [24] Dietrich T *et al.* 2018 (Preprint [1804.02235](#))
- [25] Nagar A *et al.* 2018 *Phys. Rev. D* **98** 104052 (Preprint [1806.01772](#))
- [26] Blanchet L *et al.* 1996 *Class. Quant. Grav.* **13** 575–584 (Preprint [gr-qc/9602024](#))
- [27] Damour T, Jaranowski P and Schaefer G 2001 *Phys. Lett.* **B513** 147–155 (Preprint [gr-qc/0105038](#))
- [28] Blanchet L *et al.* 2005 *Phys. Rev. D* **71** 124004 (Preprint [gr-qc/0503044](#))
- [29] Buonanno A *et al.* 2009 *Phys. Rev. D* **80** 084043 (Preprint [0907.0700](#))
- [30] Blanchet L 2014 *Living Rev. Relativ.* **17** 2 (Preprint [1310.1528](#))
- [31] Buonanno A and Damour T 1999 *Phys. Rev. D* **59** 084006 (Preprint [gr-qc/9811091](#))
- [32] Buonanno A and Damour T 2000 *Phys. Rev. D* **62** 064015 (Preprint [gr-qc/0001013](#))
- [33] Damour T, Jaranowski P and Schaefer G 2008 *Phys. Rev. D* **78** 024009 (Preprint [0803.0915](#))
- [34] Damour T and Nagar A 2009 *Phys. Rev. D* **79** 081503 (Preprint [0902.0136](#))
- [35] Barausse E and Buonanno A 2010 *Phys. Rev. D* **81** 084024 (Preprint [0912.3517](#))
- [36] Damour T and Nagar A 2016 *Lect. Notes Phys.* **905** 273–312
- [37] Pretorius F 2005 *Phys. Rev. Lett.* **95** 121101 (Preprint [gr-qc/0507014](#))
- [38] Campanelli M *et al.* 2006 *Phys. Rev. Lett.* **96** 111101 (Preprint [gr-qc/0511048](#))
- [39] Baker J G *et al.* 2006 *Phys. Rev. Lett.* **96** 111102 (Preprint [gr-qc/0511103](#))
- [40] Mroue A H *et al.* 2013 *Phys. Rev. Lett.* **111** 241104 (Preprint [1304.6077](#))
- [41] Husa S *et al.* 2016 *Phys. Rev. D* **93** 044006 (Preprint [1508.07250](#))
- [42] Chu T *et al.* 2016 *Class. Quant. Grav.* **33** 165001 (Preprint [1512.06800](#))
- [43] Schutz B F 2011 *Class. Quant. Grav.* **28** 125023 (Preprint [1102.5421](#))
- [44] Fairhurst S 2011 *Class. Quant. Grav.* **28** 105021 (Preprint [1010.6192](#))
- [45] Abbott B P *et al.* 2017 *Astrophys. J.* **848** L12 (Preprint [1710.05833](#))
- [46] Abbott B P *et al.* (LIGO Scientific, Virgo) 2019 *Astrophys. J.* **875** 161 (Preprint [1901.03310](#))
- [47] Abbott B P *et al.* (LIGO Scientific, Virgo) 2019 *Astrophys. J.* **882** L24 (Preprint [1811.12940](#))
- [48] Nitz A H *et al.* 2019 (Preprint [1910.05331](#))
- [49] Nitz A H, Capano C, Nielsen A B, Reyes S, White R, Brown D A and Krishnan B 2018 (Preprint [1811.01921](#))
- [50] Venumadhav T, Zackay B, Roulet J, Dai L and Zaldarriaga M 2019 (Preprint [1904.07214](#))
- [51] Zackay B *et al.* 2019 *Phys. Rev. D* **100** 023007 (Preprint [1902.10331](#))
- [52] LIGO Scientific Collaboration, Virgo Collaboration 2018 GWTC-1 <https://doi.org/10.7935/82H3-HH23>
- [53] Racine É 2008 *Phys. Rev. D* **78** 044021 (Preprint [0803.1820](#))
- [54] Veitch J *et al.* 2015 *Phys. Rev. D* **91** 042003 (Preprint [1409.7215](#))
- [55] Özel F, Psaltis D, Narayan R and McClintock J E 2010 *Astrophys. J.* **725** 1918–1927 (Preprint [1006.2834](#))
- [56] Farr W M *et al.* 2011 *Astrophys. J.* **741** 103 (Preprint [1011.1459](#))
- [57] Woosley S E 2017 **836** 244 (Preprint [1608.08939](#))
- [58] Marchant P *et al.* 2018 (Preprint [1810.13412](#))
- [59] Apostolatos T A, Cutler C, Sussman G J and Thorne K S 1994 *Phys. Rev. D* **49** 6274–6297
- [60] Kidder L E 1995 *Phys. Rev. D* **52** 821–847 (Preprint [gr-qc/9506022](#))
- [61] Abbott B P *et al.* (LIGO Scientific, Virgo) 2019 (Preprint [1903.04467](#))
- [62] Lattimer J M and Prakash M 2016 *Phys. Rept.* **621** 127–164 (Preprint [1512.07820](#))
- [63] Flanagan E E and Hinderer T 2008 *Phys. Rev. D* **77** 021502 (Preprint [0709.1915](#))
- [64] Abbott B P *et al.* (LIGO Scientific, Virgo) 2019 *Phys. Rev. D* **X9** 011001 (Preprint [1805.11579](#))
- [65] Abbott B P *et al.* (LIGO Scientific, Virgo) 2018 *Phys. Rev. Lett.* **121** 161101 (Preprint [1805.11581](#))
- [66] Abbott B P *et al.* (LIGO Scientific, Virgo) 2019 (Preprint [1908.01012](#))
- [67] Metzger B D 2017 *Living Rev. Rel.* **20** 3 (Preprint [1610.09381](#))
- [68] Abbott B P *et al.* 2017 *Nature* **551** 85–88 (Preprint [1710.05835](#))
- [69] LIGO Scientific, Virgo Collaboration GraceDB URL <https://gracedb.ligo.org/superevents/public/03/>
- [70] Akutsu T *et al.* (KAGRA) 2019 *Nat. Astron.* **3** 35–40 (Preprint [1811.08079](#))
- [71] Abbott B P *et al.* (KAGRA, LIGO Scientific, VIRGO) 2018 *Living Rev. Rel.* **21** 3 (Preprint [1304.0670](#))